AUDIO DELAY LINE

RIXON ENGINEERING BULLETIN No. 88

# A VERSATILE DELAY EQUALIZER

*The Data System Engineer Must Solve the Problems of Delay Distortion in Voice Circuits to Make Them Suitable for High Speed Data Communications.*

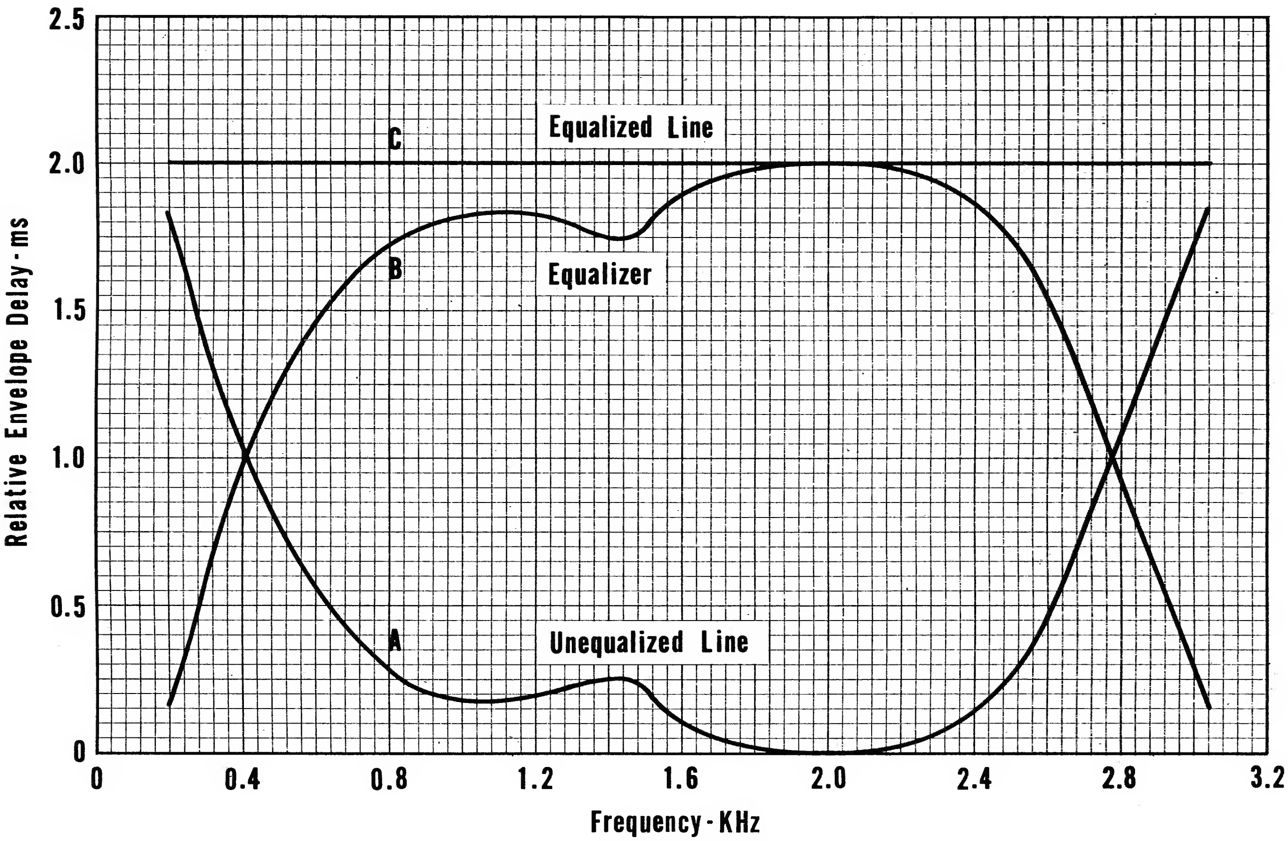


*Figure I. Delay Characteristic of a Voice Circuit and Correction.*

## Making Voice Paths Equal to the Task of Data Communications

Every morning on the way to work you are probably reminded that our highways were never meant to shoulder today's heavy traffic. In hopes of making the road system work better new improvements are made everyday.

It is the same with data communications. The usual pathways for data are telephone lines created for voice and are not quite up to the needs of machine communications. To be equal to the task the voice paths must be improved.

To do it the data system engineer employs delay equalization. It is to data communications what a freeway is to the highway system.

## The Problem

In order to bring a telephone line up to the quality required for a data communications system the delay characteristic must be equalized or corrected. A plot of the delay characteristic of a line would be similar to curve A, figure 1. The line is equalized by correcting the delay curve to make it flat or constant with respect to frequency. This is accomplished by adding a series network which has the opposite or complementary delay characteristic. Curve B, figure 1 is a plot of such a delay complementary characteristic.

By adding the network in series with the original line the composite circuit or equalized line having a flat delay characteristic is obtained as illustrated by curve C, figure 1.

This correction would make the line suitable for high speed data communication.

This is the basic problem and solution. It seems simple. But there are a number of elements in the problem that make it complex.

First, there is a class of problems associated with the realization of the delay characteristic of figure 1-B. Since, in the general problem presented above, we have placed no limit on the given curve A, there is no limit to the shape required of curve B. Even if we place certain limits on the maximum deviation of curve A, as is so often done in specifications for delay equalizers, we are still faced with the fact that curve A may have <u>any</u> slope and thus requires that curve B have an equal and opposite slope. Intuitively we realize that this is not possible with a finite number of real networks. Therefore there will be certain limitations to the shape of curve B which can be obtained — even before we consider the nature of networks available to generate curve B.

We have not considered the amplitude characteristic of the given line as yet. If, to simplify the problem, we consider only the delay characteristic, it must nevertheless be apparent that the networks making up the delay characteristic of curve B must be flat in amplitude. Simple lead-lag networks or tuned circuits cannot be used to generate the delay function because they also have their own characteristic amplitude functions.

There is only one class of network which can be used to generate the delay correction characteristic, the all-pass network. An all-pass network will have a flat amplitude response if perfectly implemented. However, perfection comes no easier here than elsewhere. Perfection in this case would require zero loss components; that is, capacitors with a dissipation factor of zero and inductors with infinite Q.

If we now consider the restricted class of networks remaining, we find the basic delay characteristics of all all-pass networks are similar. A set of delay characteristics for such an all-pass network is shown in figures 2, 3 and 4. Figure 2 is for a network tuned to 600 cycles while figures 3 and 4 show the characteristic for the same network tuned to 1600 cycles and 2800 cycles respectively. The network shown here is an active circuit with an adjustable delay. The numbers 1, 5 and 10 on the curves correspond to three different settings of a continuous control.

There are several important features to be noted from these curves. First these curves are typical of all all-pass networks whether active or passive. There are differences in the delay characteristics of various all-pass networks but they are minor.

Note that the curves do not simply scale down in delay. There is, instead, a definite change of shape with control setting. The delay characteristic gets broader as the peak delay is lowered. This is a fundamental characteristic resulting from the fact that the total phase shift from zero to infinite frequency remains constant (at 360° for the network shown). It is obvious that one limiting factor on our ability to obtain any correction curve is tied to this fixed relationship between slope of delay characteristic and maximum delay.

It should also be noted that the higher the delay peak for a given network, the more difficult it will be to maintain constant amplitude. Thus the amplitude limitation discussed above results in a limitation of the range of adjustment of the network which may be used.

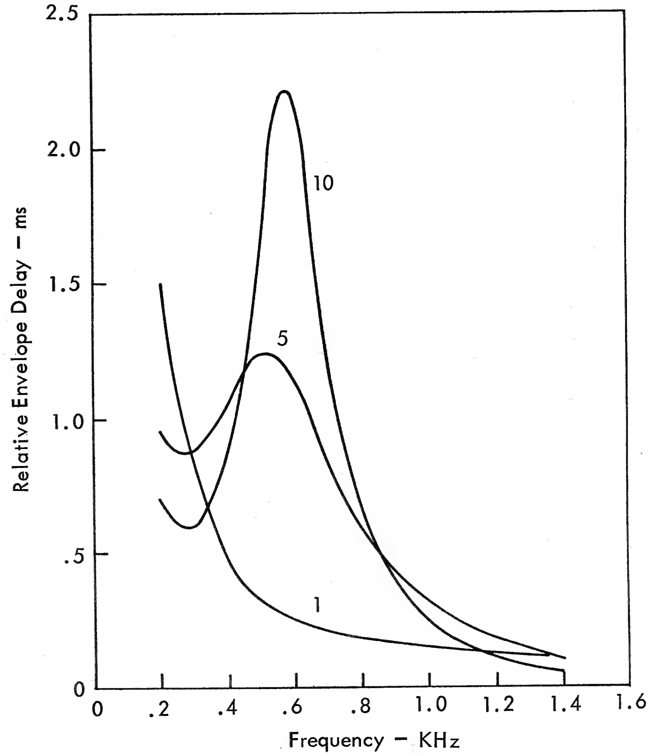


*Figure 2. 600 cps Section Delay Characteristic.*

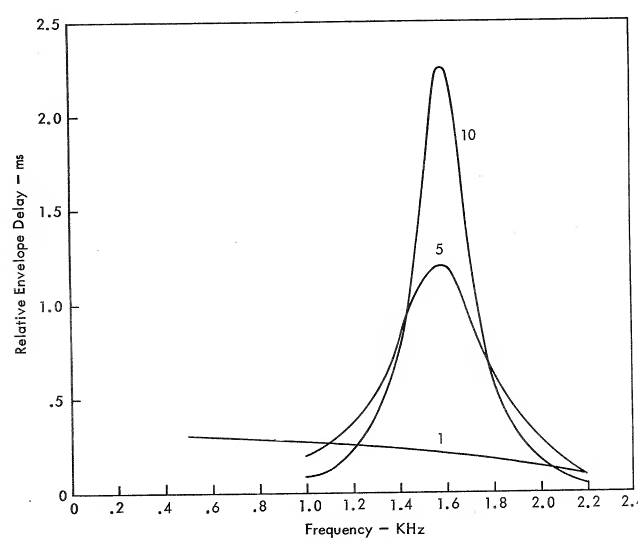


*Figure 3. 1600 cps Section Delay Characteristic.*

Another important feature of the delay characteristics (figures 2, 3 and 4) is the lack of symmetry. In figures 4 and 3 this lack of symmetry may not be obvious without careful study but it is pronounced in figure 2. This lack of symmetry is <u>not</u> due to faulty implementation or to non-perfect components. It is, rather, a basic characteristic of all all-pass networks. It can be minimized by the proper selection of basic network configuration. It does not help a bit in implementing a delay characteristic to correct a given line.

Another factor, not obvious in the figures, but which can be shown mathematically or by careful large scale plotting, is when two or more such networks are connected in series so that their delay characteristics add, the resultant composite delay characteristic will not necessarily be flat. In other words, the shape of the curves are not such that a perfectly flat delay curve will be obtained in the overlap region between the peaks of the adjacent networks. In general, the resultant composite delay curve does tend to become flatter as the amount of overlap increases.

This, of course, says that the conditions for maximum flatness or freedom from ripple are opposed to those for correcting steep slopes in the given curve.

Now two final points along these lines. It may be obvious from what has been stated above that the larger the absolute amount of delay which must be corrected (the maximum deviation of the given delay characteristic between specified limits of frequency), the greater the problem of ripple will be. If we attempt to correct too great a relative delay, we may find that the correct all-pass networks themselves have introduced a ripple in the composite or "corrected" delay characteristic that is greater than the system equalization tolerance. Furthermore, the number of all-pass networks required increases in direct relation to the amount of delay which must be corrected and the bandwidth over which it must be possible to make the correction.

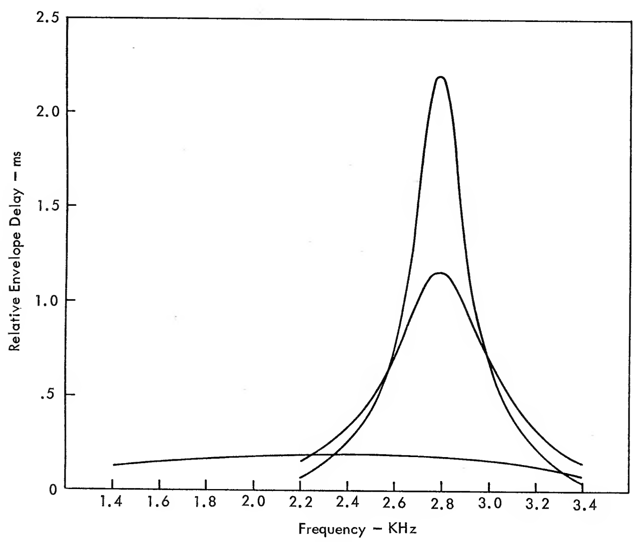


*Figure 4. 2800 cps Section Delay Characteristic.*

The foregoing discussion, while not complete, illustrates that class of problems which are associated with the realization of a given delay correction characteristic. There are, however, other problems to be considered.

One of these problems is related to the original delay characteristic for the given line (figure 1-A). How is this characteristic obtained and to what accuracy? One might also ask how the corrector characteristic B is to be measured. However, we will see that the problem of measuring a passive or active delay corrector is less severe than that of measuring the original line.

The factor which introduces the greatest problem in the measurement of the delay characteristic of a real line is frequency translation. Since most long line telephone service is provided by carrier facilities, the lines of interest to the data communications system engineer will almost invariably exhibit some degree of frequency translation. The effect of this is to make each discrete frequency component of an input waveform (A sin $\omega$ t) be recovered at the receive end of the line with a small offset $\Delta\omega$. (A sine ( $\omega + \Delta\omega$ ) t) The offset $\Delta\omega$ is the same for all frequencies in the band. The effect is to make it impossible to measure the phase response directly. This is the principle difference between the problem of measuring the actual line and that of measuring a correction network. The correction network does not in general exhibit frequency offset and a direct phase measurement may be made.

A detailed consideration of the functioning of a delay measuring set designed to operate over real lines having input and output separated by large distances is beyond the scope of this paper. It should be noted here, however, that the measurement is not a simple one to make, that it requires some method of obtaining a measurement reference at the receive end, and that accuracies of greater than 50 u sec are not generally claimed.

A third class of problems to be considered is related to the mechanism for obtaining the correction delay characteristic needed. Assume that an accurate curve of envelope delay vs frequency for the given line has been obtained. This curve may be inverted to yield the delay corrector curve required. Further assume that we have designed a finely incremented range of suitable all-pass networks having the sort of curves shown in figures 2, 3 and 4. How, then, will we select and combine the necessary networks to provide the best equalization. (We have already established that a perfect equalization may not be possible.)

If we consider first the actual physical method of combining, we see that many variations are possible. We might select fixed networks from a large selection and permanently wire these into the circuit. Or, we might use a smaller number of variable or adjustable networks permanently wired together to make up an adjustable equalizer. The possibilities are endless – but unfortunately – they are all compromises of the various factors of desirability which might be considered.

If it is selected to use a group of adjustable sections connected together to form an adjustable delay equalizer, we still must determine what degree of adjustment to provide. Each network might be adjustable in frequency and in peak delay – but should these factors be adjustable by increment or continuously – to how fine a degree and over what range. Furthermore, what about ganging controls vs separate controls.

All of these engineering decisions are, in fact, compromises between the factors of cost, complexity, degree of correction sought, and ease of operation.

That last item – ease of operation – is a complex problem in itself. This is so because it leads us to still another area of discussion. How will we actually make the adjustment? (Whether it is made by network selection or by adjustable networks, we must make an adjustment and then determine if the desired result has been reached.) The adjustment can be made with successive alternation of measurement – adjustment – measurement – adjustment using a delay set to measure the entire circuit including the delay corrector. The corrector is adjusted until the

composite line measurement falls within the specification limits. The adjustment can also be made by monitoring the data modem in actual operation and adjusting for the least distortion in the recovered modulation. This is called the "eye pattern" method since the recovered modulation may best be observed by synchronizing the oscilloscope with the receive clock and viewing many overlapping traces which form an eye shaped pattern.

The "eye pattern" method provides an easy and quick adjustment but does not assure any given limits on the delay curve. This is another subject which is too extensive to cover here. However, the reader is referred to another paper by the author which discusses the problem in some detail.[1/]

In summary, we see that the problem is not one but many inter-related problems most of which do not have clean cut, black and white, answers.

Delay equalization calls for many compromises and no best single solution seems possible.

## The Solution

After just having suggested that there may not be a solution, I will proceed to present one. This solution is embodied in a delay equalizer such as a Rixon DDAE-4 shown in figure 5. This equalizer, like all others known to the writer, is a compromise – and as such may not be best in all cases. However, it has been proven to be an extremely valuable tool in many data communications problems and achieves a large measure of flexibility with reasonable cost and ease of operation.

The equalizer consists of twelve active delay sections. Each section is fixed in frequency and the twelve sections are distributed evenly across the frequency band. Each section has a separate delay control. This allows adjustment of delay in each segment of the band. Each section control has a switch which operates at extreme CCW rotation to remove the section completely.

The individual active sections employed in this equalizer represent a significant improvement over those employed in earlier model Rixon delay equalizers and in equalizers of other makes. First, they provide a more nearly flat amplitude response even at high delay settings and second, they provide a delay characteristic having less "skew" (more symmetrical) than that provided by earlier models.

The actual measured delay characteristics for three selected sections are shown in figures 2, 3 and 4 referred to earlier.

The number of sections used reflects considerations of many factors. A lower limit on the number of sections required can be found from the basic equations:

$$Td + \frac{d\phi}{d\omega}$$

If we assume a constant delay across the frequency band –

$$Td + \frac{\Delta\phi}{\Delta\omega}$$

1/ "Delay Distortion in Telephone Lines" – 1961 IRE International Convention Record, Volume 9, Part 8, page 109.

If we now define the intended use of the equalizer by stating that we expect to correct delay up to 3 ms across the band from 400 to 3000 cps, we have fixed:

$$Td = 3 \text{ ms}$$
$$\Delta\omega = 2600 \times 2\pi \text{ radians}$$

Rewriting and inserting these values

$$\Delta\phi = Td \times \Delta\omega$$
$$= 3 \times 10^{-3} \times 2600 \times 2\pi$$
$$\Delta\phi = 7.8 \times 2\pi \text{ radians}$$

Now, since each section contributes $2\pi$ radians of phase shift, we see that a minimum of 8 sections are required.

However, there are other factors to consider. The most significant of these are the magnitude of the delay and amplitude ripple which will be acceptable in the equalized line.

As already stated in the first section of this paper, the shape of the delay vs frequency curve for each section is not ideally suited to the concept of combining sections to obtain a flat delay. A flatter delay is obtained when the delay sections are not adjusted for high Q but are allowed a significant degree of overlap.

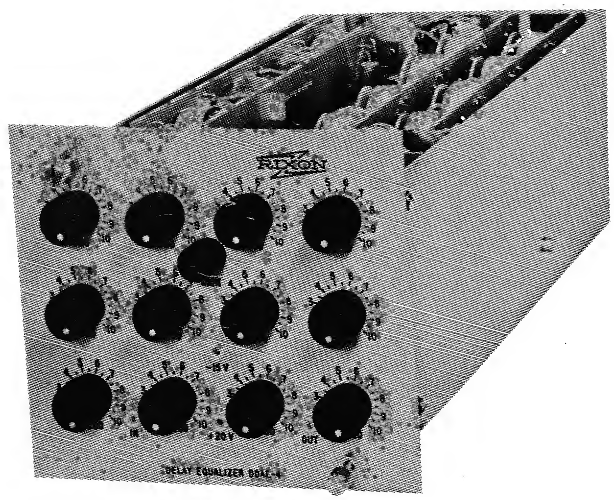


*Figure 5. DDAE-4, Delay Equalizer.*

Futhermore, the amplitude response of each section shows a greater departure from the flat condition as the Q of the section is increased.

When limits of 80 us on delay ripple and $\pm 1$ db on amplitude are established for the overall performance of the equalizer, we find that the number of sections required is increased from 8 to 12.

Once the number of sections had been established, the question of the number or type of controls vs variability to be provided for each section was considered. Basically each section can be varied in center frequency and Q or peak delay at center frequency. Since twelve sections were to be used in a band of 2600 cycles, it was felt that fixed frequencies would be adequate. In other words, with the sections spaced across the band, there would be a section approximately every 200 cps and frequency adjustment could be obtained in effect by simply selecting the sections nearest the point at which it was desired to add delay.

Therefore the center frequencies of the sections are evenly spaced across the band and are not adjustable.

Now the number of delay controls had to be considered. It is possible to adjust delay across the entire band with one control. In other words, we might gang the controls of all 12 sections and provide only one operator control. Or, we might combine the controls of 2, 3, 4 or 6 sections to provide 6, 4, 3 or 2 controls respectively.

This is obviously a question of balancing simplicity and ease of adjustment, which results from a minimum of controls; with maximum flexibility and greatest equalizing ability which results from twelve separate controls.

The Rixon DDAE-4 was intended to provide accurate equalization of lines where other equalizers had failed. Maximum flexibility was required. Therefore, twelve separate controls are provided and each control regulates the amount of delay in a portion of the spectrum centered around the center frequency of its section.

Each section's delay control was provided with a switch which removes delay sections completely when the control is turned fully CCW. This feature effectively removes one of the greatest objections to an equalizer having 12 separate controls. It is not necessary to adjust all twelve controls in most cases. One simply turns all sections off (which leaves only a constant delay or linear phase amplifier in the circuit) and uses only those sections corresponding to a portion of the band where added delay is required.

Many times only one or two sections are required and often it is possible to obtain a better correction with only one or two sections than could be obtained by using all sections.

This key feature of this equalizer means that it is not always a 12 control equalizer - but it may be so in the extreme case where this is required.

The question of operational use was touched on briefly in the section above on the "problem." There are basically two different ways in which an equalizer such as the DDAE-4 may be employed to solve the data communication system problem of delay equalization. It can equalize the delay characteristic of a given line, so that, after equalization, the delay characteristic falls within specified limits. Or, it may be employed to correct the line so that a given data modem performs within the system limits.

Let's first consider delay equalization to given limits. If this choice is followed, it is necessary that some form of delay measuring equipment be employed. The first step in the procedure is to measure the delay characteristic of the line. With currently available delay sets, this is a rather tedious process which requires a technician at each end of the line to be measured and a voice communications link or "order wire" in addition to the line being measured. The result of such a measurement is a column of figures for delay vs frequency. These figures may be studied in tabular form or plotted as a graph to determine if the delay characteristic is within acceptable limits. If it is not, the shape of the measured curve will serve as a guide to the delay correction required. If the line curve shows a dip at – say 1000 cps – then the delay control for 1000 cps should be advanced to insert delay at that frequency.

Several variations are possible at this point. If both transmit and receive portions of a delay set are available at the site, the technician may elect to connect the delay set to the delay equalizer alone and adjust the equalizer until a delay characteristic measured through the equalizer alone is obtained which is the complement of that of the line and would therefore be expected to correct it to a constant delay. The equalizer is then connected in series with the line and the "corrected line" remeasured to assure that equalization within the set limits has been achieved.

Or the technician may elect to connect the equalizer directly to the line and make adjustments while measuring the composite of real line and equalizer. The advantage of this method is that once the equalizer is adjusted, the job is complete and the final checking measurement of the first method is not required. However, if the line is a difficult one to correct, the first method may require less time since measurements made locally are much easier and quicker to make than those made over the real circuit. Obviously, one may combine the two methods.

What about delay equalization to obtain specified modem performance? In this method of equalization one is not concerned with an actual measurement of the delay characteristic of the line either before or after correction.

The modem to be employed in the system is connected to each end of the line and random data introduced at the modulator or transmitter. Some modems have a random data source as a built in feature. No further operator attenation is required at the transmitter.

At the demodulator or receiver an oscilloscope is used to view the demodulated or recovered data (prior to decision making). A scope sync is obtained from the receive clock (clock phasing having been recovered by the modem). The result is many over-lapping traces of the recovered random digital data in band limited form. This is the "eye pattern," so named because of its resemblance to the human eye.

When the modem is first connected to the line, the received eye pattern may be so poor as to be barely recognizable. The delay equalizer, connected in series with the modem and line, is now adjusted to improve the eye pattern. That is, to make the pattern look more nearly as it does when the modem is operating back to back or with a perfect line.

The adjustment is basically one of trial and error. However, anything that is known about the line characteristic or the modem may make the true problem something less than pure trial and error.

Even the likelihood that this is a normal line is helpful in that we expect the line characteristics to have the typical U shape. We know therefore that we will need to add more delay in midband than at either end. Of course any more exact information we may have about the location of dips or bumps in the delay characteristic will further reduce the range of likely settings of the delay equalizer controls.

Knowledge of the modem which we possess is also

helpful in that we know the modem is more sensitive to variations in envelope delay near the carrier frequency. Starting with adjustments of delay near the carrier frequency will often make the trial and error process easier.

The principle advantage of this method is that it is fast, effective and requires little extra equipment.

The principle disadvantage is that when the adjustment has been made so good performance results, no knowledge of the corrected line characteristic is available. This may not be immediately apparent but it stems from the fact that variation in conventional envelope delay normally specified for data lines is not directly related to distortion in the recovered modulation. The relationship is rather complex and a given degree of "eye pattern" distortion may result from an unlimited number of different delay characteristics.

The first section of this paper discusses the basic problem of delay distortion as it affects the data communication system. In the second portion, a delay equalizer has been discussed which, while admittedly not perfect, has proven to be an extremely valuable tool in many data communications systems. And finally, the use of such a delay equalizer has been discussed and the relative merits of two different methods of use considered.

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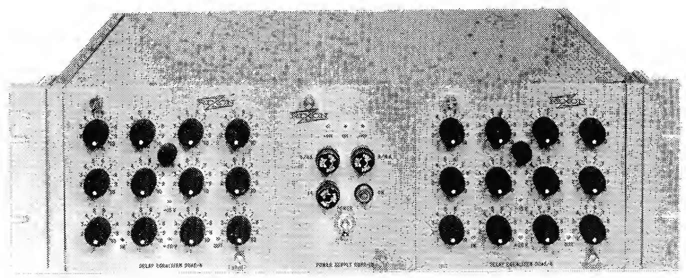
Additional copies available from Rixon Electronics, 2120 Industrial Parkway, Silver Spring, Maryland 20904

# TELEPHONE LINE DELAY EQUALIZER 4007

*A Versatile Unit to Equalize Telephone Lines to Make Them Suitable for High Speed Data Communications*



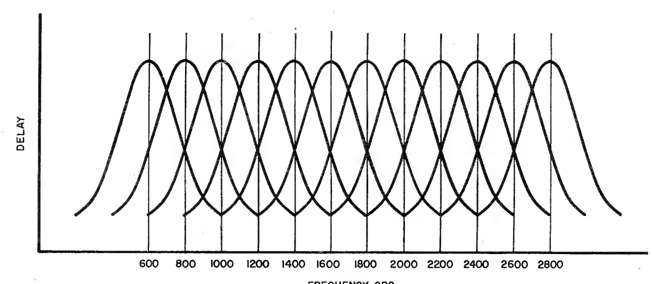
DESCRIPTION: The DD4007 Telephone Line Delay Equalizer provides compensation for delay distortion over the entire bandwidth of a telephone line to make it suitable for high speed data transmission. The DD4007 equalizer is available in two versions. One consists of two DDAE-4 delay equalizer modules and a DDPS-10 Power Supply. It is used to correct distortion in two voice circuits having different transmission characteristics so a data system can be used with either line without adjustment. A second version consists of only one DDAE-4 equalizer module and a power supply.

ENTIRE BANDWIDTH CONTROL: The DDAE-4 equalizer modules provide a minimum of 3 ms delay covering the entire bandwidth from 600 cps to 2800 cps. Twelve separate controls allow precise correction of a given line delay characteristic by providing separate control for the delay added to each 200 cps segment of the frequency spectrum. Additional flexibility is provided by a switch on each control to bypass a delay section entirely.

An amplifier is included in each DDAE-4 to enable the line signal levels to be adjusted by means of a front panel gain control. The gain can be adjusted over a range from -10 db to +30 db.

MODULAR CONSTRUCTION: Since both the equalizer modules and the power supply are solid state devices, the DD4007 requires a minimum of vertical rack space. The complete unit shown in the photograph requires only 5-1/4 inches of vertical space. The modules are normally installed in rack mounting enclosures (DDME-1) which are designed for standard 19-inch equipment racks. Consequently, the intrarack wiring is completed at the factory and only the normal interconnections between the line and the associated equipment are left for the installer.

All external connections to the modules are through the rear panel connectors of the modules, and all modules are held in place by front panel captive screws so that they can be quickly and easily removed from the enclosure.




For flexibility the controls of the DDAE-4 equalizer modules in the DD4007 provide equalization for each 200 cps segment of the telephone circuit bandwidth for 600 cps to 2800 cps.

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